TMT High-Contrast Imaging with NFIRAOS/IRIS

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Abstract. The thirty meter telescope (TMT) has the potential to find new and to study in greater detail nearby planetary systems. It could also possibly image super-Earth planets around the closest stars or still accreting distant protoplanets in very young star forming regions. Since no first generation dedicated exoplanet finding instrument has been selected for the TMT, initial direct exoplanet imaging will have to rely on the NFIRAOS facility adaptive optics (AO) system and IRIS spectro-imaging near-infrared (NIR) camera. End-to-end Fresnel NFIRAOS/IRIS simulations are presented using their current optical designs to evaluate the system multi-wavelength high-contrast imaging capabilities. Long exposures have been simulated using the expected AO-delivered phase screens and the estimated speckle lifetime. It is shown that NFIRAOS/IRIS may achieve contrasts comparable to the Gemini planet imager (GPI, an optimized NIR planet-finding instrument that will soon be installed on the Gemini South 8-m telescope), but needs to rely on multi-wavelength processing (by a factor 50) to achieve that goal, a challenging requirement. Without a coronograph and a better treatment of the in-band static speckle noise, NFIRAOS/IRIS will not be able to achieve GPI-like high contrast at a very small inner working angle, which is potentially accessible with a large 30-meter telescope. However, TMT, with its bigger aperture and better angular resolution, along with the current NFIRAOS/IRIS designs will acquire higher SNR spectra and will achieve an astrometric accuracy three times smaller than GPI for medium to bright planets, resulting in better atmospheric characterization and faster orbital parameter determination of a sample of GPI planets.

1 Introduction

In the past, the construction of bigger telescopes and general use facility instruments were sufficient to pave the way to great new discoveries. This reality is changing with the development of highly specialize instruments that are optimized for very specific science cases. The first adaptive optics (AO) system was installed on large 10-m class telescope more than a decade ago. Since then, the ground-based exoplanet community has mostly been using these first generation AO systems along with general use near-infrared (NIR) cameras to perform dedicated direct imaging exoplanet surveys to probe the frequency of Jovian planets $> 10AU$ around nearby young stars. Hundred of hours have been dedicated to these surveys, and for the first time, direct light from young Jupiter-like exoplanets have been detected [1–4]. In parallel to these surveys, the instrumental exoplanet community made enormous progress in understanding the limits to high-contrast imaging and to design highly optimized instruments, such as the Gemini Planet Imager (GPI)[5]. GPI consists of a combination of low aberration optical elements, a high-order deformable mirror AO system, a coronagraph, a calibration interferometer and an NIR integral field spectrograph, and is expected to improve the contrast by two orders of magnitude. It is an interesting question to wonder how the thirty meter telescope (TMT), a telescope three times bigger, with a general use AO system and an NIR camera/spectrograph can perform compare to these dedicated highly optimize instruments installed on smaller 10-m class telescopes. A clear example of this reality is the Palomar high-contrast imaging of the HR 8799 system, where three of the four planets were detected using a well-corrected coronagraphic 1.5m sub-aperture [6], reaching contrast levels approaching those obtained with the 10-m KeckII telescope general AO/NIR camera.

In this paper, an end-to-end Fresnel propagation analysis of the TMT NFIRAOS/IRIS system is performed to evaluate its high-contrast imaging performance relative to currently operating instruments on 10-m telescopes and upcoming GPI. Several possible upgrades are presented to improve the system exoplanet imaging capabilities.

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2 The End-to-End PROPER Simulation

The high-contrast imaging capabilities of the TMT/NFIRAOS/IRIS system are estimated by using their current optical designs and the PROPER Fresnel wavefront propagation IDL code [7]. The PROPER software does a near- or far-field wavefront propagation that simulates the chromatic phase and amplitude aberrations mixing of out-of-pupil-plane optics[8]. This chromatic aberration mixing produces an enhanced speckle chromaticity that can prevent high level of speckle suppression when analyzing the data with sophisticated speckle subtraction algorithms. The simulation goal is to estimate the achievable contrast of a typical 1.5h observing sequence by generating time-evolving polychromatic point spread functions (images are processed by a simultaneous spectral differential imaging algorithm (SSDI)[9]). Due to the difficulty of properly simulating the time-stability of the PSF at a given wavelength, the angular differential imaging technique (ADI)[10] is not used.

An on-axis thin-lens model of the TMT/NFIRAOS/IRIS system was first defined in PROPER, including phase and amplitude aberrations on each surfaces following a -2 power-law. For the TMT telescope, 100, 60 and 40 nm RMS of mid-frequencies phase aberrations (3-20 cycles per pupil) along with 0.2% amplitude errors were assumed for respectively M1, M2 and M3. The TMT central obscuration, the secondary support shadows and segment gaps (using the gray pixel approximation) were also included. The simulated M1 mirror with its corresponding phase error is shown in Fig. 1

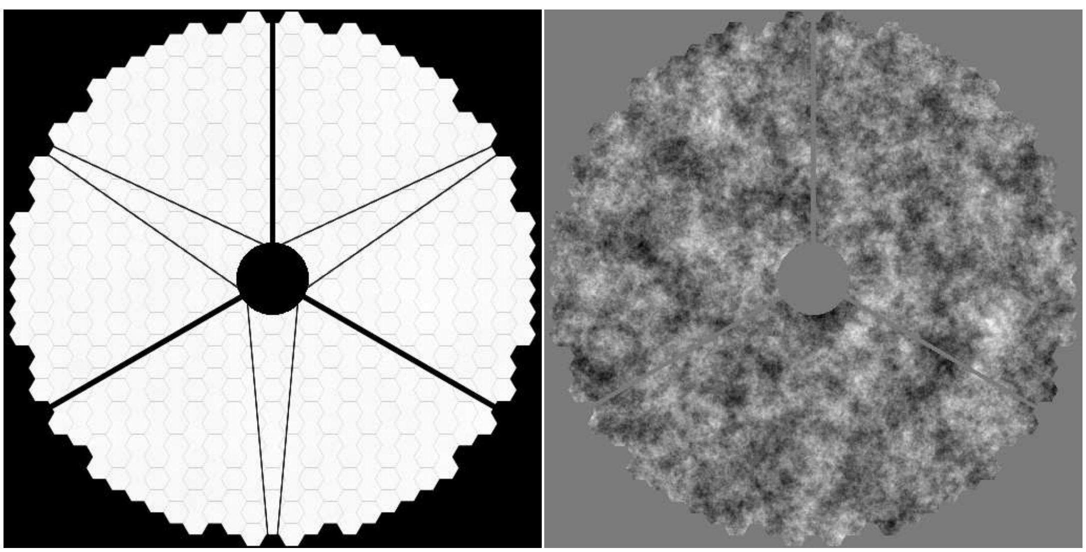

Fig. 1. The simulated TMT M1 mirror (left) and its static phase aberration (right). Independent segment aberrations were not simulated since they were generating issues with the basic wavefront sensing algorithm used for the simulation presented in this paper (see below).

For NFIRAOS optics, 26 nm RMS of mid-frequencies phase aberrations and 0.1% amplitude errors were assumed for each optics while the IRIS camera is currently assumed to be aberration free (given that it has only 30nm RMS total, the equivalent of a single NFIRAOS optics, it is expected that IRIS optics will not contribute much to the overall contrast analysis compare to TMT and NFIRAOS). The adaptive optics corrections (estimated at 0.8 micron) were applied by attenuating the estimated wavefront phase aberration power spectrum in a pupil-conjugated plane to 0 for the deformable mirror correctable spatial frequencies. The aberrations were evaluated in a simulated pupil plane after NFIRAOS focus to account for the phase retrieval correction. The individual M1 segment aberrations had to be removed from this simulation as these were producing phase discontinuities artefacts in the simple Fourier-based wavefront sensing algorithm used in this analysis (these additional aberrations will be considered in a follow-up paper). Wavefront sensing aliasing is introduced by folding back the high spatial frequencies inside the AO control radius. Given that the AO corrections are performed in the visible (0.8 micron) while the science camera is operating in the NIR, beam visible/NIR offsets have been included, proportional to the amount of estimated atmospheric refraction and each optical surface conjugated height. Finally, differential field rotation between IRIS, NFIRAOS and TMT are included to introduce some amount of speckle time-variability (all optical aberrations are currently assumed static).

A 1.5h observing sequence of a Dec = 0 star observed through transit on Mauna Kea was simulated (see Fig. 2). Residual atmospheric phase aberrations (after AO correction) were simulated with a −2 power-law of 140nm RMS (AO residuals are estimated from NFIRAOS end-to-end simulations). A random atmospheric phase screen was generated for every 0.1s of exposure while one rotation realization of the static aberrations was generated for every 30s (all aberrations are static, but they are rotated related to each other as the field rotates depending if the static aberrations are in the TMT or NFIRAOS rotation plane). For these simulations, IRIS was left stationary (not tracking the TMT pupil or NFIRAOS).

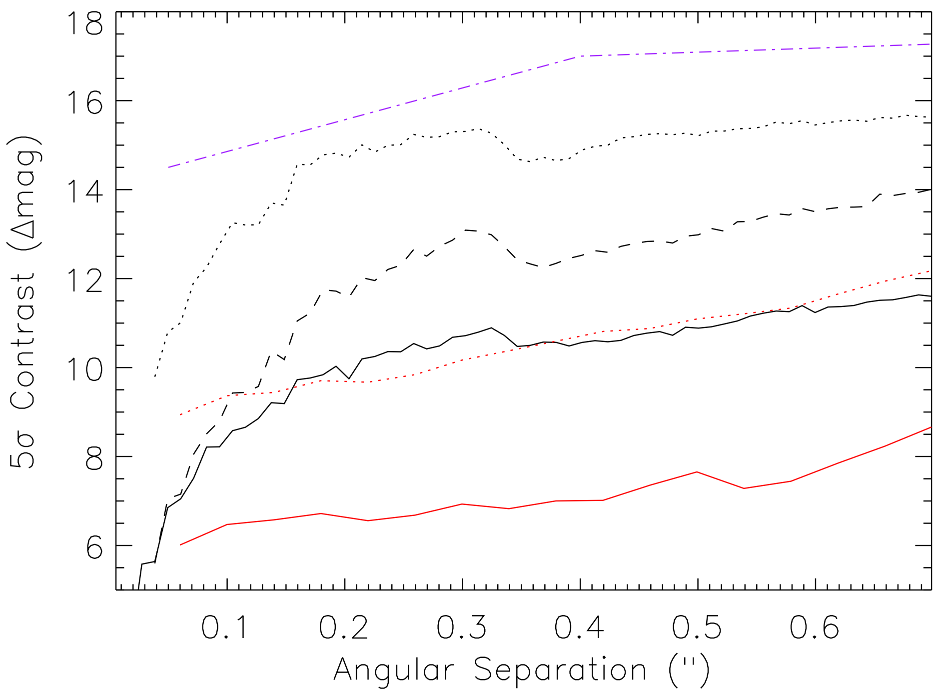

Fig. 2. TMT/NFIRAOS/IRIS 5 sigma detection limits as a function of angular separation. The thick black solid line is the NFIRAOS/IRIS detection limit for a single wavelength (1.6 micron) 30s exposure, the thick dashed line is the contrast after a 1.5h observing sequence and the dotted line is the 2h contrast after SSDI processing of two wavelengths (1.59 and 1.63 micron). The purple dot-dashed line shows the 1h GPI contrast limit. For comparison, the two red lines are the K-band contrast (H and K contrasts are similar) for a single KeckII NIRC2 exposure (solid line) and after 1h of ADI (dotted line) on HR 8799.

A 30s NFIRAOS/IRIS exposure is roughly equivalent to 1h of ADI at KeckII. After averaging images for 1.5h, the contrast goes down by ~2 magnitudes. To reach GPI-level contrast (~17 magnitudes at separations greater than 0.4 arcsec), a gain of ~50 is required. From the simulation, a gain of ~10-20 is theoretically possible by SSDI processing of two adjacent wavelengths (1.59 and 1.63 micron). While contrast gains of 20-100 (3-5 magnitudes) is reached with ADI at KeckII with NIRC2

AO and Gemini with Altair/NIRI, it is not obvious how such technique will work at TMT as the current level of aberrations for the TMT (~100-150nm RMS) and NFIRAOS (~100 nm RMS) before AO corrections are similar, resulting in significant interference between the two aberration planes after AO correction as the field rotates. The differential rotation between the two planes is producing a highly variable ”boiling” speckle pattern, so it is expected that the ADI technique will only achieve very limited gains. Less NFIRAOS (and/or telescope) aberrations would be required to stabilized the speckle pattern, allowing for better ADI speckle subtraction.

From the estimated performance, NFIRAOS/IRIS should easily achieve a 2.5 magnitude gain compare to existing 10-m facility-class instruments. Against an optimize instrument like GPI, it will be hard for TMT/NFIRAOS/IRIS to study at higher SNR or to improve the astrometry of the faintest GPI planets. Contrasts of the order of 15 magnitudes at separations greater than 0.2 arcsec (30-50 times better than KeckII, but 10 times worse than GPI) could be reached with the SSDI processing, but would require a speckle subtraction performance of the order of 20 at small separations, while current instruments using this technique have only achieved less than 5 (TRIDENT@CFHT, NICI@Gemini south and OSIRIS@KeckII). To maximize the speckle suppression efficiency of this technique, non-pupil plane conjugated aberrations should be minimized. Nonetheless, planets that have similar brightness as the HR 8799 planets will definitely be feasible with NFIRAOS/IRIS as well as a sample of medium brightness Jovian planets that GPI should find. In addition, fainter targets (nearby M stars or more distant targets, possibly up to nearby very young associations) that are not observable with GPI (GPI magnitude limit is ~ 8 in I-band while NFIRAOS is 14) will also be scientifically interesting targets and will gain from the increase resolution.

3 NFIRAOS/IRIS High-Contrast Imaging Upgrades

Several possible upgrades were studied to try to improve NFIRAOS/IRIS contrast. With the current level of residual aberrations, a simple coronagraph would not improve the current predicted performance while requiring significant redesign of the instruments to enable access to the needed pupil and focal planes. Static aberrations would first need to be reduced and/or corrected with the deformable mirror using an in-band NIR calibration unit, similar to how the GPI CAL system[11] is feeding back in near real time the in-band quasi-static speckle information back to its deformable mirror. Once the in-band aberrations have been lowered, to achieve a dark hole with a coronagraph, a spatial filter[12] would need to be implemented in NFIRAOS. The ADI technique could be used to improve the current contrast, but the fact that we have multiple rotation planes will limit the technique. NFIRAOS and IRIS would need to track the TMT pupil but this is not currently possible (only IRIS can tract TMT for a limited FOV rotation range). Even if all these systems would be implemented, diffraction from the secondary obscuration and its support shadows would rapidly be a limiting factor and would need to be dealt with a pupil apodization to minimize their impact on the focal plane.

Instead of trying to improve the contrast at shorter NIR wavelengths, another possible approach is to keep the current design and improve the sensitivity to lower mass planets by going at longer wavelengths, like Lp, where planets are brighter, thus at lower contrasts relative to the stellar primary. The current NFIRAOS window and beam-splitter coating is blocking the Lp flux. In addition, IRIS currently does not have a detector sensitive to Lp and compatible optics. From simply scaling from Keck Lp observations, ie assuming a similar emissivity and thus a background 10x fainter due to the larger aperture, NFIRAOS/IRIS could detect lower mass planets than GPI on nearby stars. As an example, on HR 8799 GPI could reach down to 1.5 Jupiter masses at K-band (30 Myr star at 40 pc) in 1h while TMT at Lp (see Fig. 3 for a simulated 2h Lp sequence), could go down to half a Jupiter mass.

Assuming a speckle suppression gain of a few at smaller separations, TMT could challenge or even do better than GPI down to 0.1 arcsec separation (approximately GPI inner working angle). A more in-depth study of various possible NFIRAOS/IRIS high-contrast imaging upgrades will be presented in a follow-up paper.

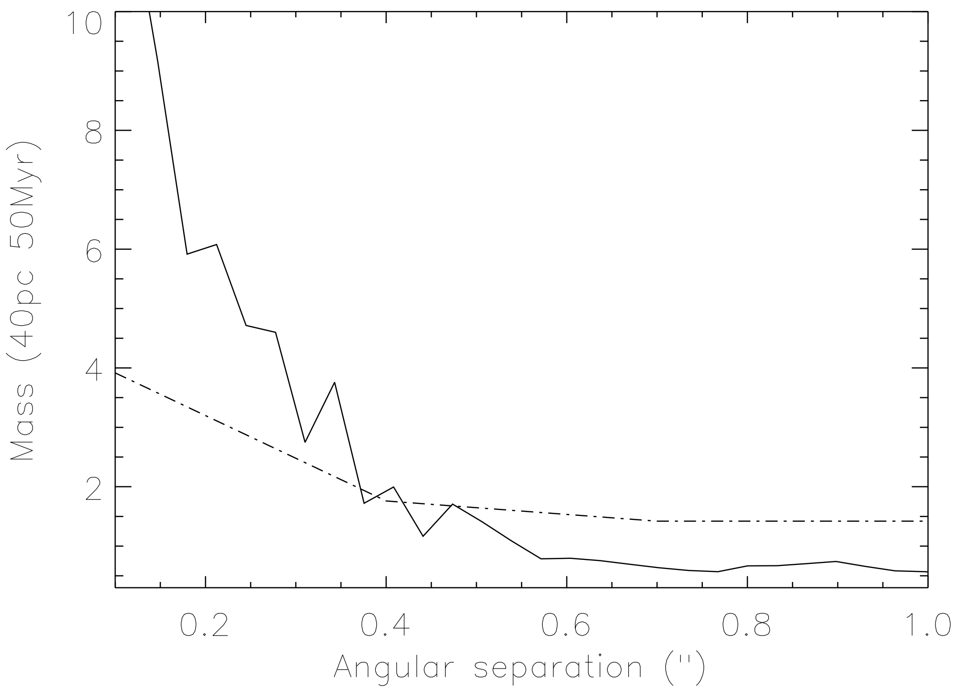

Fig. 3. A simulated 2h HR 8799 observation with NFIRAOS/IRIS at Lp with no speckle subtraction (note that the current NFIRAOS/IRIS designs do not allow for such observations). Planets down to half a Jupiter mass could be detected, reaching a better mass sensitivity limit than GPI.

4 Conclusions

An end-to-end wavefront simulation was presented of the TMT/NFIRAOS/IRIS system. It was shown that better performance (13 mag at 0.5 arcsec) will be achieved, more than 2 magnitudes better, than existing general-use AO and NIR instruments on 10-m telescopes (10.5 mag at 0.5 arcsec). After SSDI processing, contrasts of the order of 15 magnitudes could be reached at 0.5 arcsec. Compare to GPI, an optimized high-contrast imaging instrument for the Gemini 8m telescope, NFIRAOS/IRIS will not reach similar contrast levels unless a gain of a factor 50 is obtained by SSDI processing, a challenging requirement. The existence of several rotation planes will generate speckle boiling that will probably limit the possible gains by ADI.

Several possible upgrades were studied individually, but they were all giving limited to no gain unless they would all be implemented to produce a dark hole. To obtain a competitive instrument compared to GPI, instead of trying to improve the contrast at shorter wavelengths, one solution would be to go to longer wavelengths, Lp, where planets are brighter and easier to detect. The lower TMT background would allow for the detection of planets less massive than what GPI can detect at shorter wavelengths.

In the era of optimized instruments, TMT is not an exception. NFIRAOS/IRIS will do great exoplanet science on medium to bright HR8799-like planets by enabling higher resolution spectroscopy and better astrometry to fit orbits. To be competitive with GPI at similar wavelengths, NFIRAOS and IRIS would need some modifications to generation of a dark hole. To reach even higher contrasts, TMT will need a dedicated instrument, similar to GPI or the propose planet formation imager (PFI)[13] to improve on the GPI analysis, and detect & characterize closer-in/smaller mass planets.

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